UNIVERSITA' DEGLI STUDI DI L'AQUILA FACOLTA' DI INGEGNERIA
DISAT
L.Iam laboratorio di idraulica ambientale e marittima

"Onde di maremoto: meccanica della generazione, propagazione e interazione con le coste"

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Water waves generated by landslide in reservoirs: Italian events

A. Petaccia, A. Maistri

Research program on landslide generated water waves

*Italian Dam Office – **RID***

*Laboratory of Environmental and Maritime Hydraulic – **LIAM**- of l'Aquila University*

The evaluation of impulsive waves originated by landslides in artificial reservoirs is of the utmost importance for dams and artificial reservoirs planning and management. In artificial basins where landslide risk exists, water level is kept below the maximum level, thus avoiding dam overtopping and the run-up on the shoreline of the potential impulse wave.

Recently, the National Dam Service (now RID Registro Italiano Dighe) funded a research program, based on experimental, numerical and mathematical studies, aimed at forecasting the main parameters related to water waves generated by landslides.
The experimental investigations carried out in LIAM laboratory led to the formulation of empirical relations on the principal features of impulse water waves propagating in a three dimensional water body . Moreover a laboratory study was used to define the impulse wave run-up on plane slope.

The results of these experiments were used to determine the principal features of subaerial landslide generated waves observed during the tragic events occurred in 1959 at the Pontesei artificial reservoir, and in 1960 and 1963 at the Vajont artificial reservoir.

3D PHYSICAL MODEL
The experimental variables

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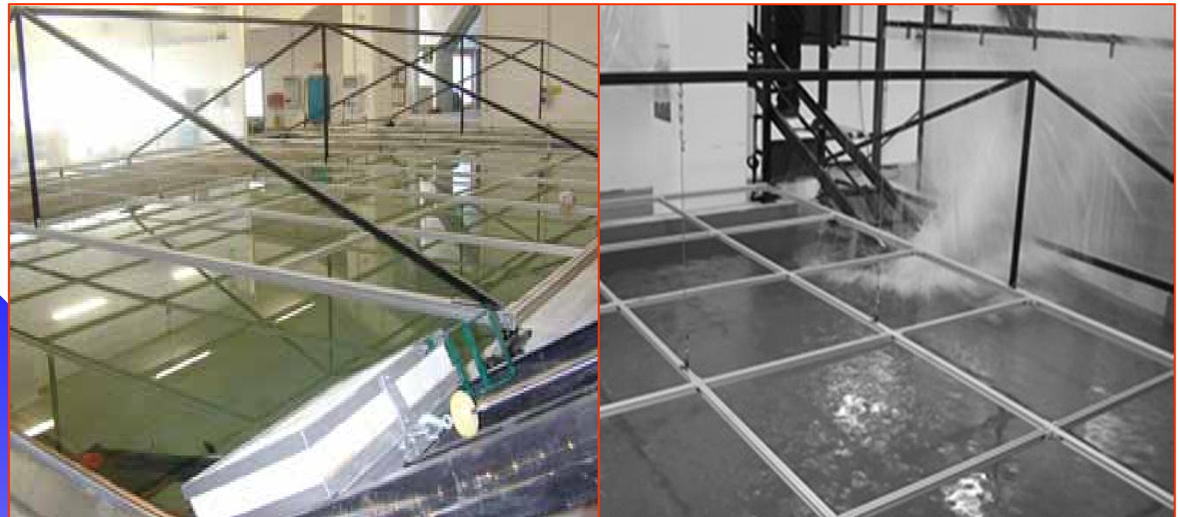
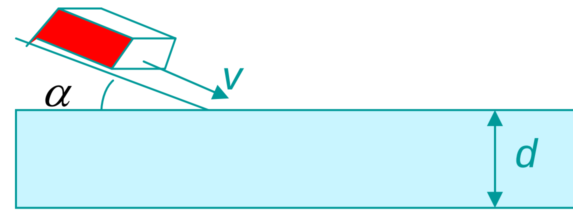
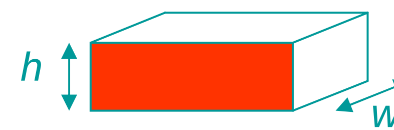


Pictures from the three dimensional physical model. On the left, solid block landslide model and wave tank. On the right, impact of the landslide model with water.

The experimental parameters

Landslide width **w** (m)
Landslide height ***h*** *(m)*
Impact velocity ***v*** *(m/sec)*
Landslide surface inclination ***α*** *(°)*
Distance from impact point ***r*** *(m)*
Angle from velocity vector ***Φ*** (°)
Local water depth ***d*** *(m)*





The landslides were modelled as solid blocks with zero porosity

Ranges of non dimensional parameters of the performed experiment

h/d	w/d	$v/\sqrt{(gd)}$	α	θ	r/d
0.11÷0.45	0.75÷3.00	0.99 ÷ 2.22	16° ÷ 26°	0° ÷ 90°	1.31÷15.12

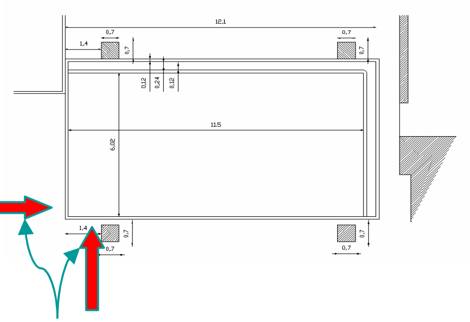
3D PHYSICAL MODEL
Experimental formulation

Size basin

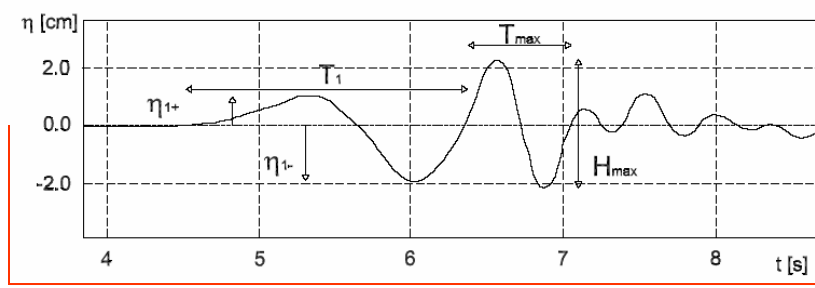
Lenght = 11.50 m

Width = 6.00 m

Depht = 0.80 m



Impact direction landslide



Maximum generated wave height

$$\left(\frac{H_{max}}{d}\right)^{*} = 0.12 \cdot \left(\frac{r}{d}\right)^{-0.4} \cdot \left(\frac{w}{d}\right)^{0.79} \cdot \left(\frac{h}{d}\right)^{0.5} \cdot \left(v/\sqrt{gd}\right)^{0.17} \cdot e^{0.6\cdot\cos\theta - 0.8\cdot\sin\alpha}$$

Wave period of maximum wave height

$$T_{max}\sqrt{g/d} = 2.5\left(\frac{h}{d}\right)^{0.1}\left(\frac{v}{\sqrt{gd}}\right)^{0.29}\left(\frac{r}{d}\right)^{0.18} e^{0.22\sin(\alpha)}$$

Wave height and period of the first water wave

$$H_1/d = 0.2(r/d)^{-0.8}(w/d)^{1.17}(h/d)^{0.88} \cdot \left(v/\sqrt{gd}\right)^{0.22} e^{1.32\cos\theta - 1.12\sin\alpha}$$

$$T_1\sqrt{\frac{g}{d}} = 6.9\left(\frac{r}{d}\right)^{0.16}\left(\frac{w}{d}\right)^{0.16}\left(\frac{h}{d}\right)^{0.16} e^{0.23\cos\theta}$$

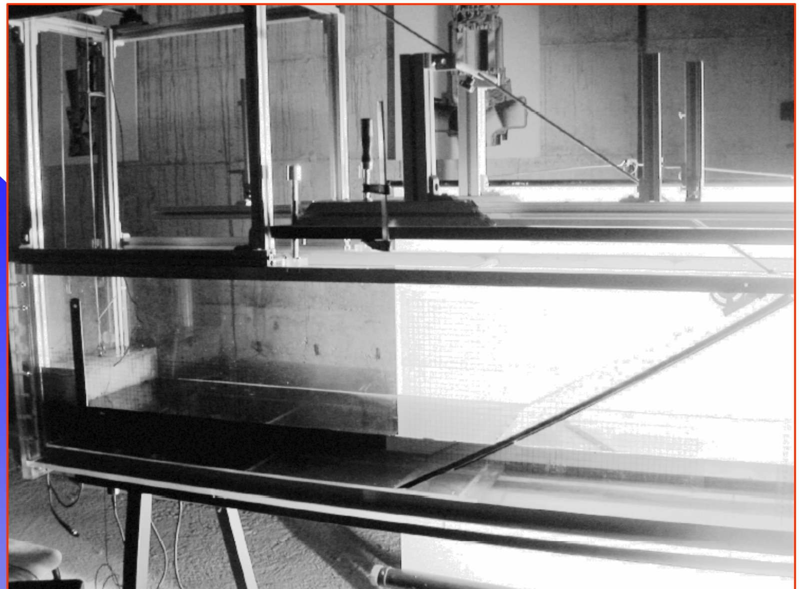
Crest and trough of the first water wave

$$\eta_{1+}/d = 0.069(r/d)^{-0.82}(w/d)^{1.28}(h/d)^{0.97} \cdot \left(v/\sqrt{gd}\right)^{0.2} e^{1.55\cos\theta - 1.4\sin\alpha}$$

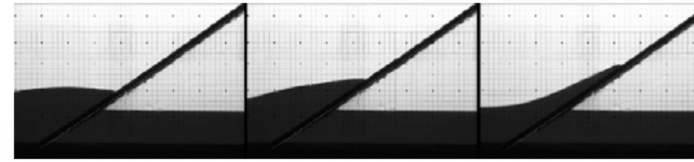
$$\eta_{1-}/d = -0.12(r/d)^{-0.82}(w/d)^{1.11}(h/d)^{0.84} \cdot \left(v/\sqrt{gd}\right)^{0.24} e^{1.21\cos\theta - \sin\alpha}$$

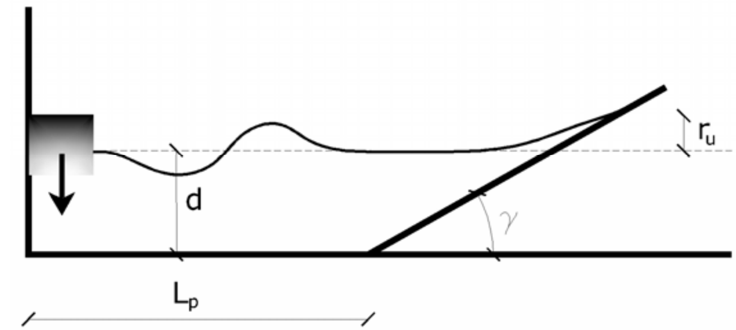
2D PHYSICAL MODEL
Experimental formulation

Wave flume



Images from one of the performed experiments on the run-up of landslide generated water waves





Sketch of the physical model used to study the run-up of landslide generated water waves on plane slopes

Experimental ranges of the considerate non dimensional variables.

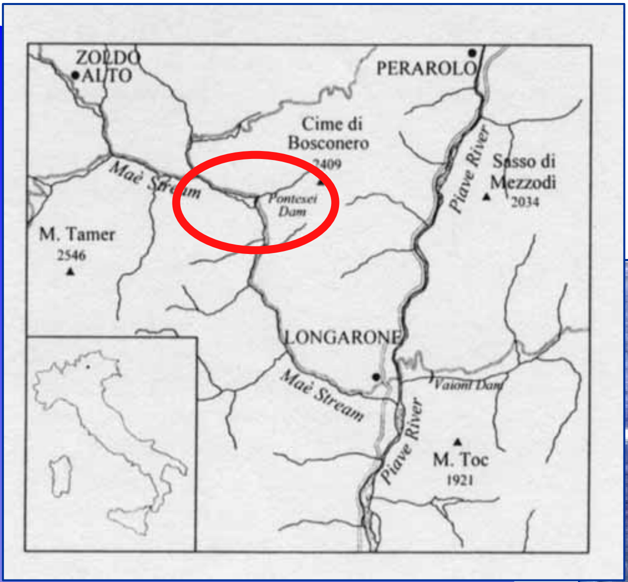
H/d	$T\sqrt{(g/d)}$	γ
0.18 ÷0.70	7.45 ÷ 15.60	19° ÷ 84°

Wave runup on the sloped plane (runup ru)

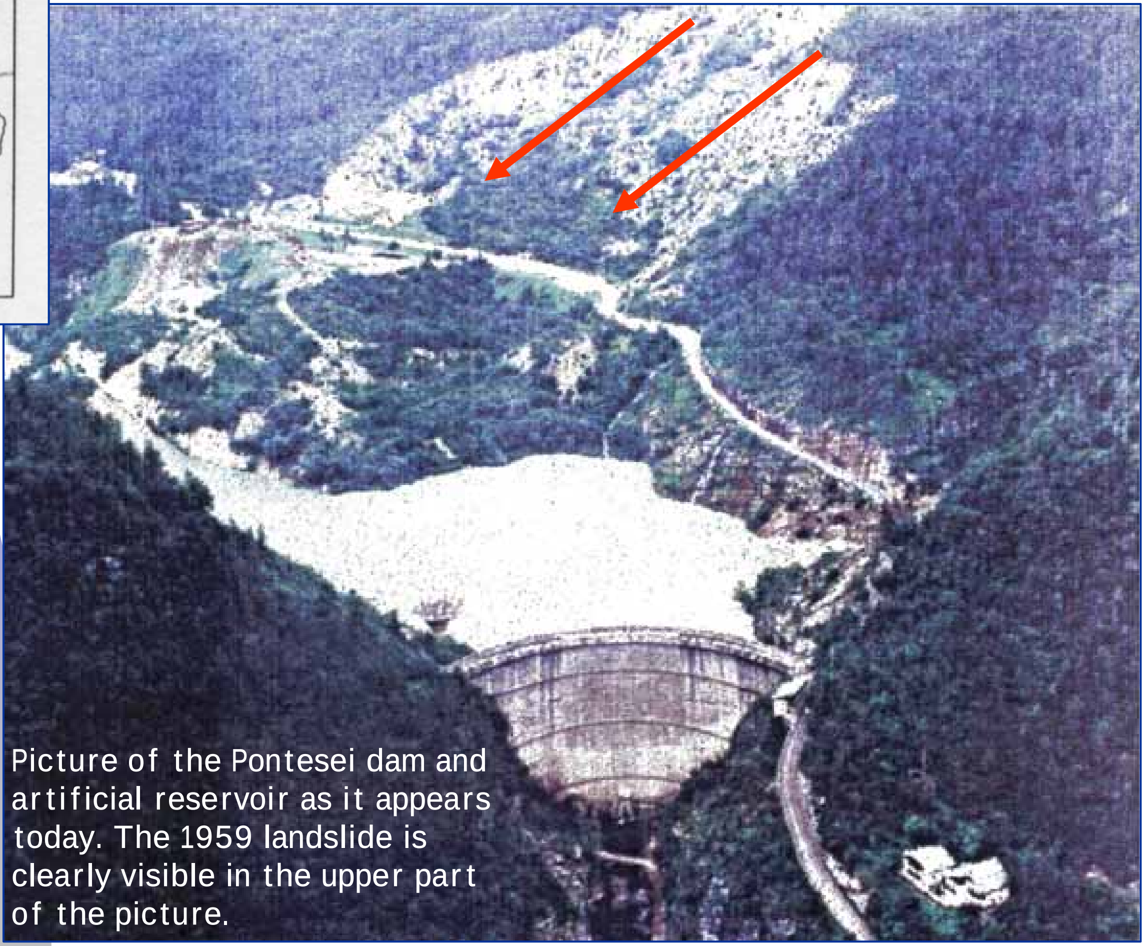
$$r_u/d = 1.37(H/d)^{1.51}\left(T\sqrt{g/d}\right)^{0.47}(\sin\gamma)^{0.26}$$

Application of forecasting formulation

Pontesei reservoir
March 22nd, 1959 event
(Southern Alps)



H dam (D.M. 24.03.82)	93,00 m
Storage capacity before the landslide event	$9.09 * 10^6$ mc
Storage capacity after the landslide event	$5.8 * 10^6$ mc



Picture of the Pontesei dam and artificial reservoir as it appears today. The 1959 landslide is clearly visible in the upper part of the picture.

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Pontesei reservoir March 22nd, 1959 event

On March the 22nd 1959, an impulsive wave was generated by the falling of a rotational slide which mobilised about 4.5-5.0 million m^3 of debris. The basin contained about 6.10 million m^3 of water A man, who was riding along the street on opposite side of the basin, was killed by the run-up of impulse water wave. The 1959 event didn't cause damages to the dam, but reduced the storage capacity of about the 50%.

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Pontesei reservoir March 22nd, 1959 event

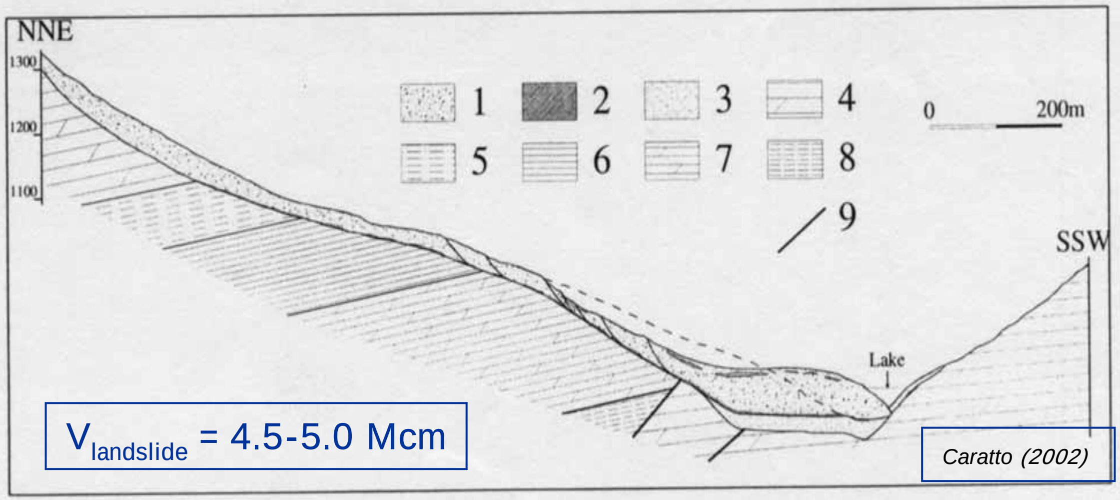

Figure 3. Geologic profile. 1) Slope debris; 2) Clayey deposit; 3) Alluvial deposit; 4) Dolomia Principale (Noric); 5) Formazione di Raibl (Upper Carnic); 6) Formazione di San Cassiano (Carnic); 7) Dolomia Cassiana (Carnic); 8) Strati di La Valle (Upper Ladinic); 9) Fault.

(Vielmo, march 23 o 24, 1959)

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Parameters introduced in the experimental formulation

Parameter	Unit	Value
Landslide width (w)	[m]	400.0
Landslide height (h)	[m]	47.0
Impact velocity (v)	[m/sec]	0.4-0.8
Local water depth (d)	[m]	47.0
Angle from velocity vector (θ)	[°]	0.00
Landslide surface inclination (α)	[°]	5-10
Distance from impact point (r)	[m]	175.0
Runup slope inclination (γ)	[°]	40

h/d	*w/d*	*v/√(gd)*	α	θ	*r/d*
0.11÷0.45 **1.0**	0.75÷3.00 **8.51**	0.99 ÷ 2.22 **0.019 ÷ 0.037**	16° ÷ 26° **5° ÷ 10°**	0° ÷ 90° **0°**	1.31÷15.12 **3.72**

Landslide non dimensional parameters

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Application of forecasting formulation

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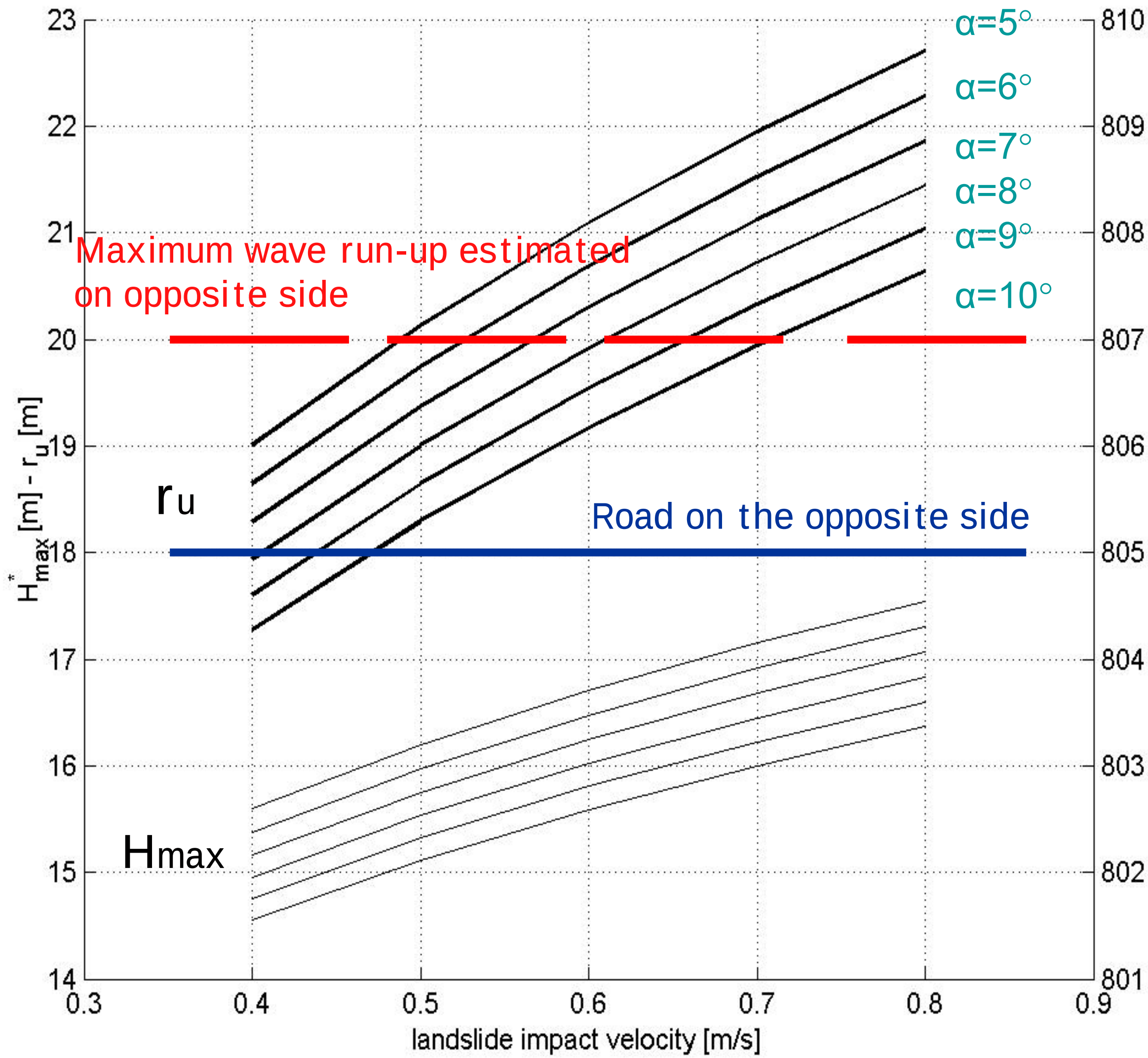
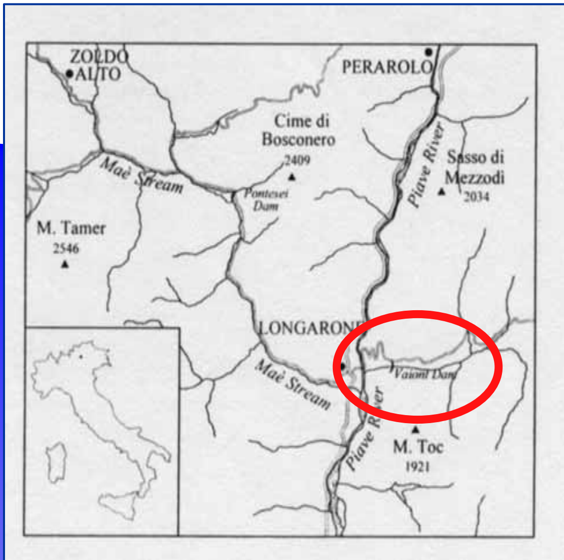
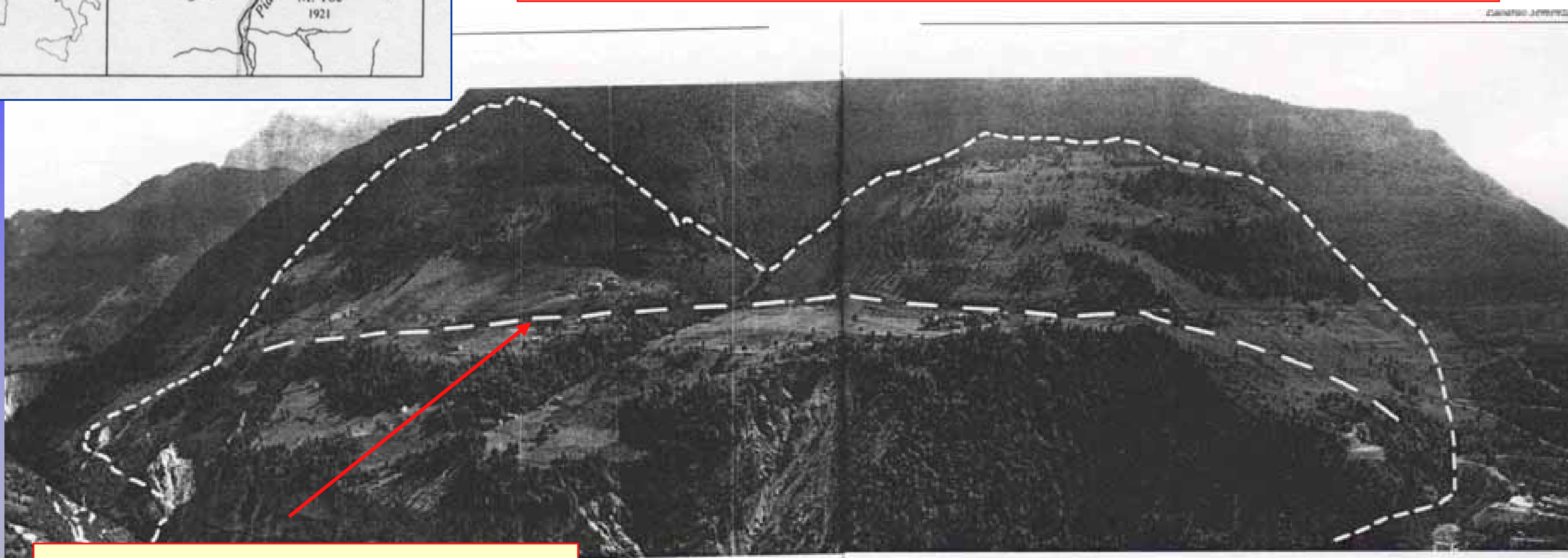
Pontesei reservoir
March 22nd, 1959 event





Vajont reservoir
Left slope of the valley (Toc mountain)

Picture of the Toc mountain, reporting the first hypothesis about dimension and shape of the landslide mechanism interesting the Vajont reservoir



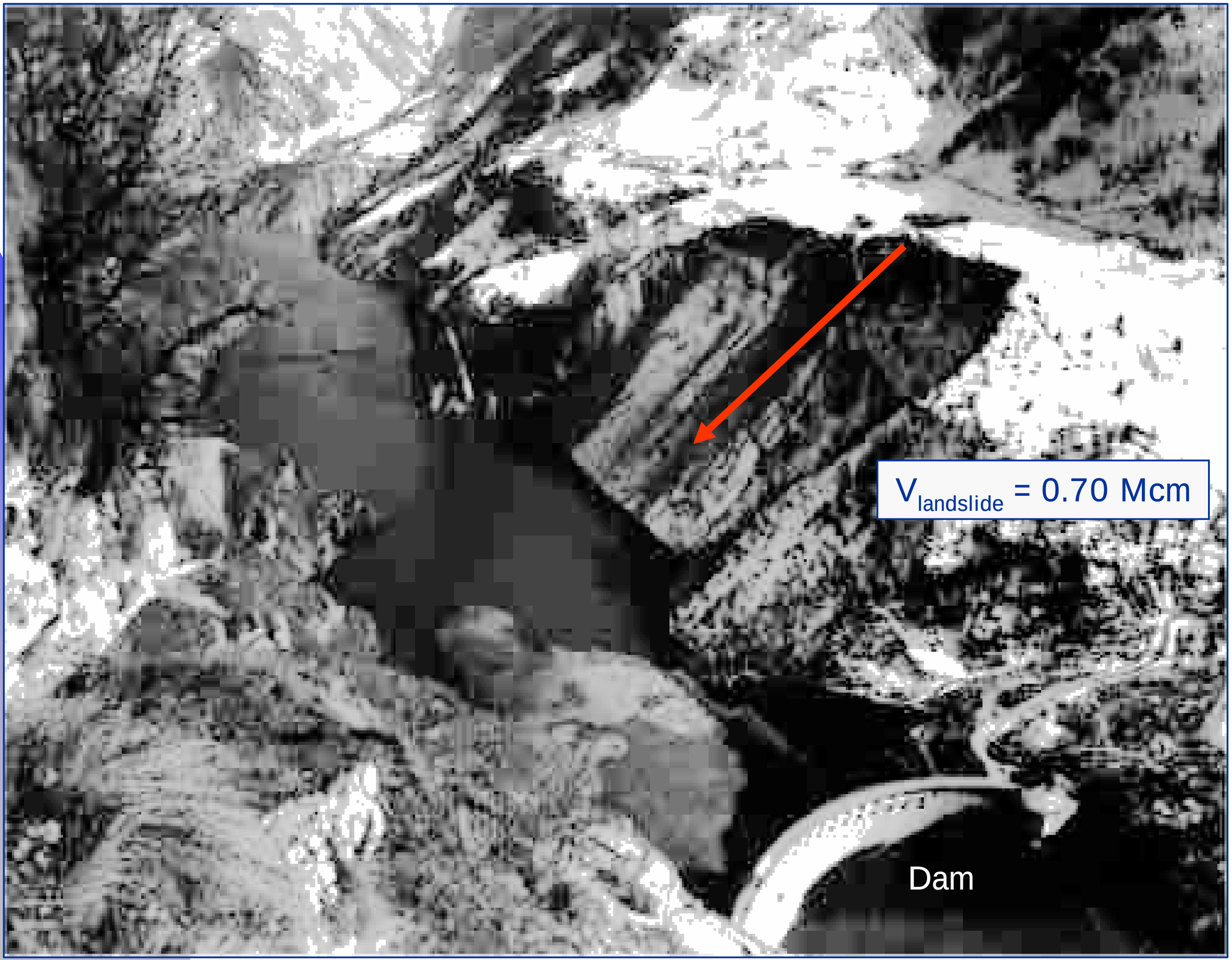
First hypothesis of paleo-slide (1959)

E. Semenza, 1959

The construction of the artificial reservoir in the Vajont valley triggered the instability of the slopes, and two rock landslides which fell into the water on November 4th, 1960 and on October 9th 1963.

Vajont reservoir
November 4th, 1960 event

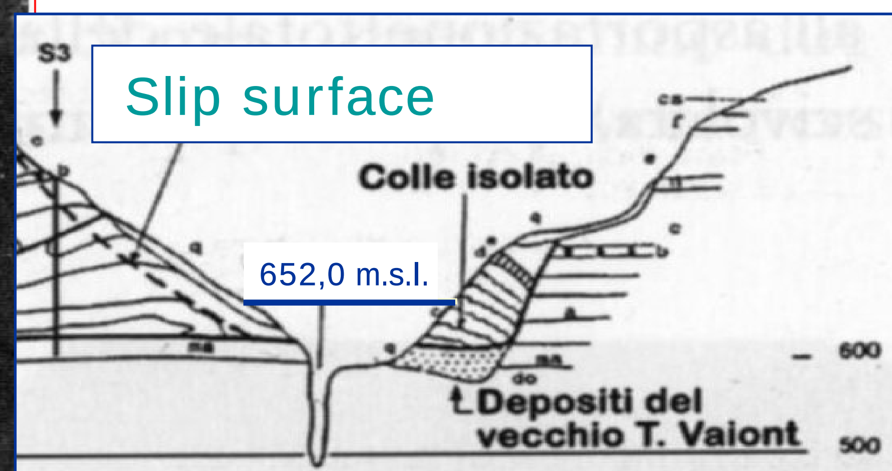
The first event occurred at the Vajont reservoir while the artificial basin was filling up for the very first time. On November 4th, 1960 a debris and rock landslide, with a volume equal to 0.70 million m^3, fell into the water causing an impulse water wave which was 2.0 m high on the dam. At that moment, the reservoir surface was at 652.00 m over the s.l., the basin had a mean water depth equal to 160 m, and contained 40 million m^3 of water. About the 1960 event no observation of wave run-up are reported.



Vajont reservoir November 4th, 1960 event

E. Semenza, april 10th, 1961

When this picture taken the water level was equal to 600,0 m.s.l.



Parameters introduced in the experimental formulation

Landslide width (w)	[m]	250.00
Landslide height (h)	[m]	7.0-10.0
Impact velocity (v)	[m/sec]	5-10
Local water depth (d)	[m]	160.00
Angle from velocity vector (v)	[°]	90.00
Landslide surface inclination (α)	[°]	30-35
Distance from impact point (r)	[m]	480.00

h/d	w/d	$v/\sqrt{(gd)}$	α	θ	r/d
0.11÷0.45 **0.04 – 0.06**	0.75÷3.00 **1.56**	0.99 ÷ 2.22 **0.13 ÷ 0.25**	16° ÷ 26° **30° ÷ 35°**	0° ÷ 90° **90°**	1.31÷15.12 **3.00**

Slide non dimensional parameters

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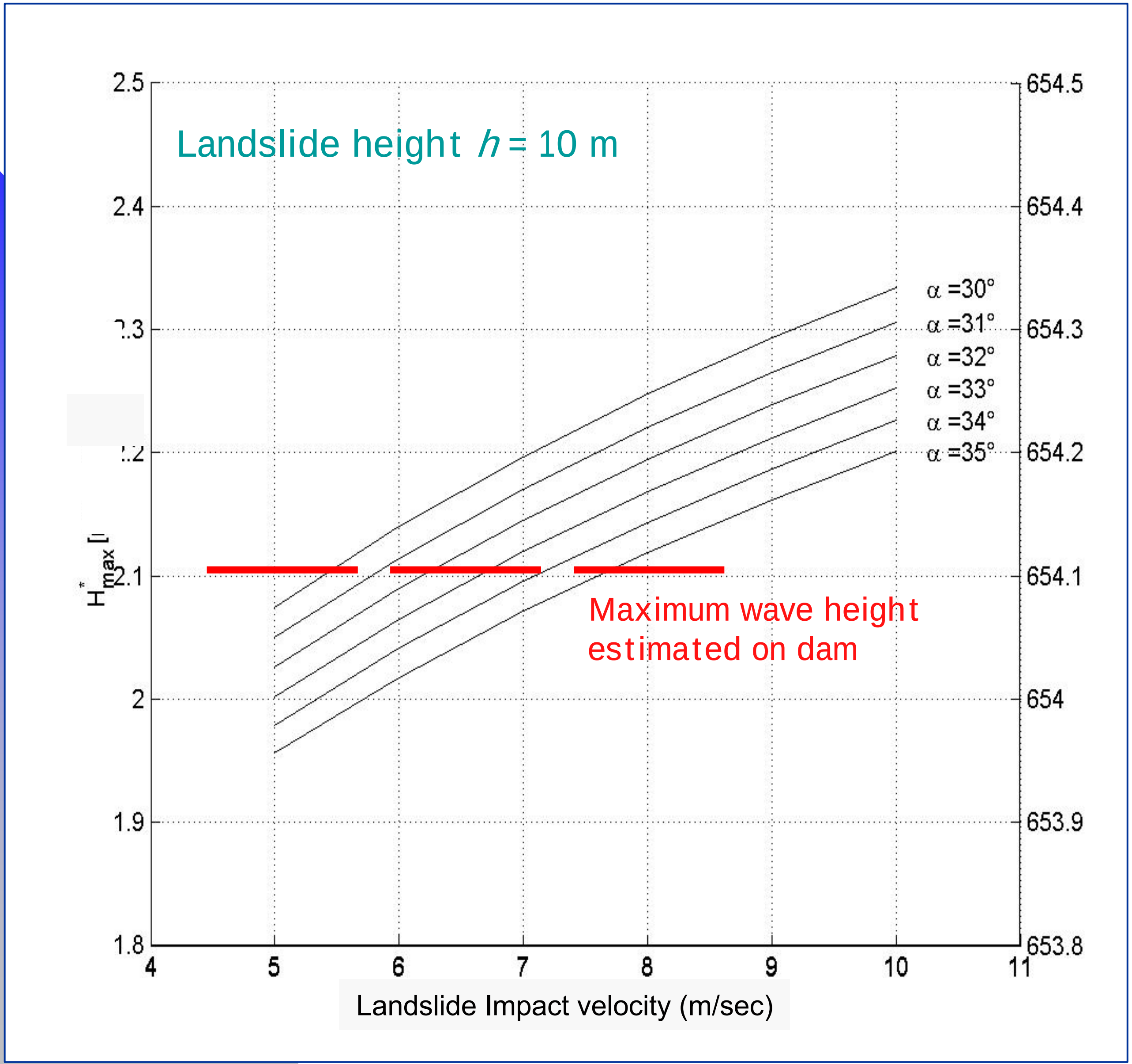
Vajont reservoir
November 4th, 1960 event



Application of forecasting formulation

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Vajont reservoir
October 9th, 1963 event

The event occurred the 9th October, 1963 is one of the most catastrophic ever documented phenomenon of sub aerial landslide generated waves.
A 270 million m^3 landslide detached from the Toc Mountain and fell into the Vajont artificial reservoir, which had been filled up during the previous years.
The 9th October, 1963 the basin surface was at 700,42 m over the s.l. , corresponding to a mean water depth equal to 200.0 m, and contained about 120 millions m^3 of water. The landslide generated a high impulse wave which run upped the opposite slope, reaching the height of 235 m above the basin water surface, right close to the city of Casso, propagated upstream the Vajon valley, and downstream, overtopping the dam and then destroying the city of Longarone, killing 2000 people.

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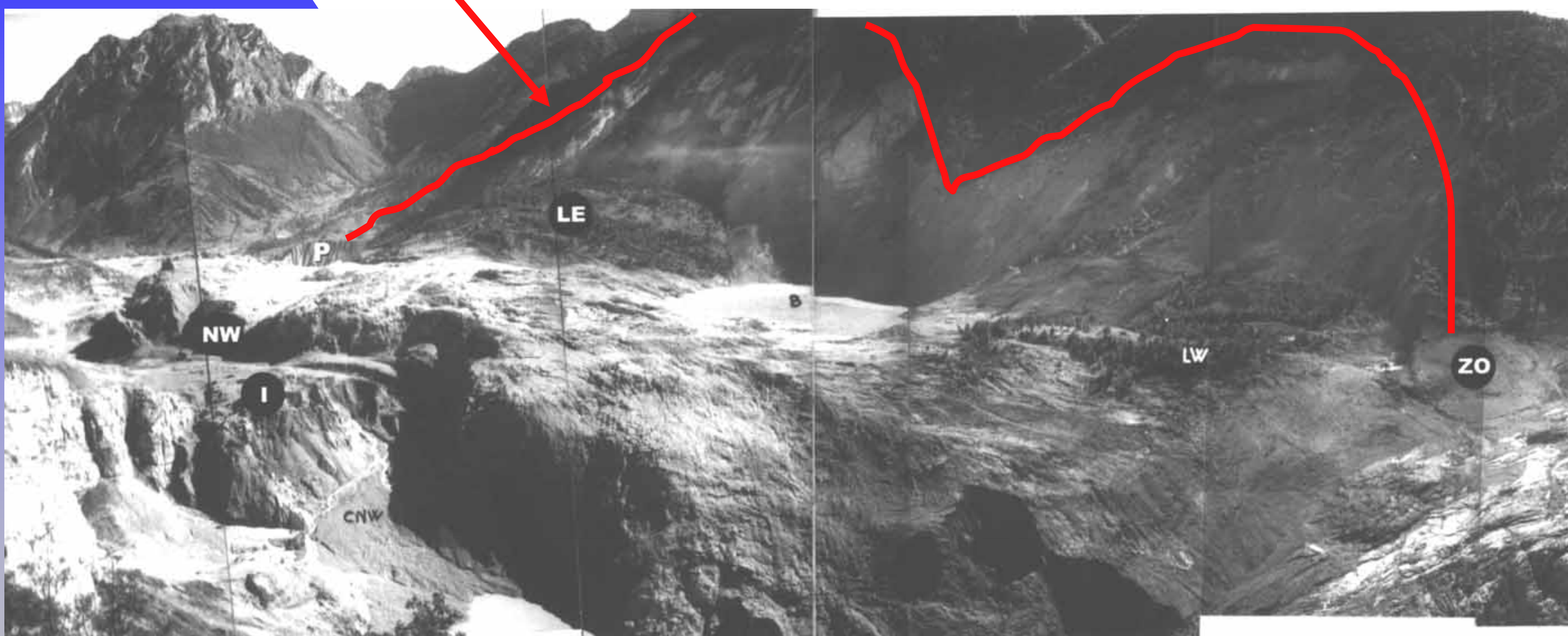
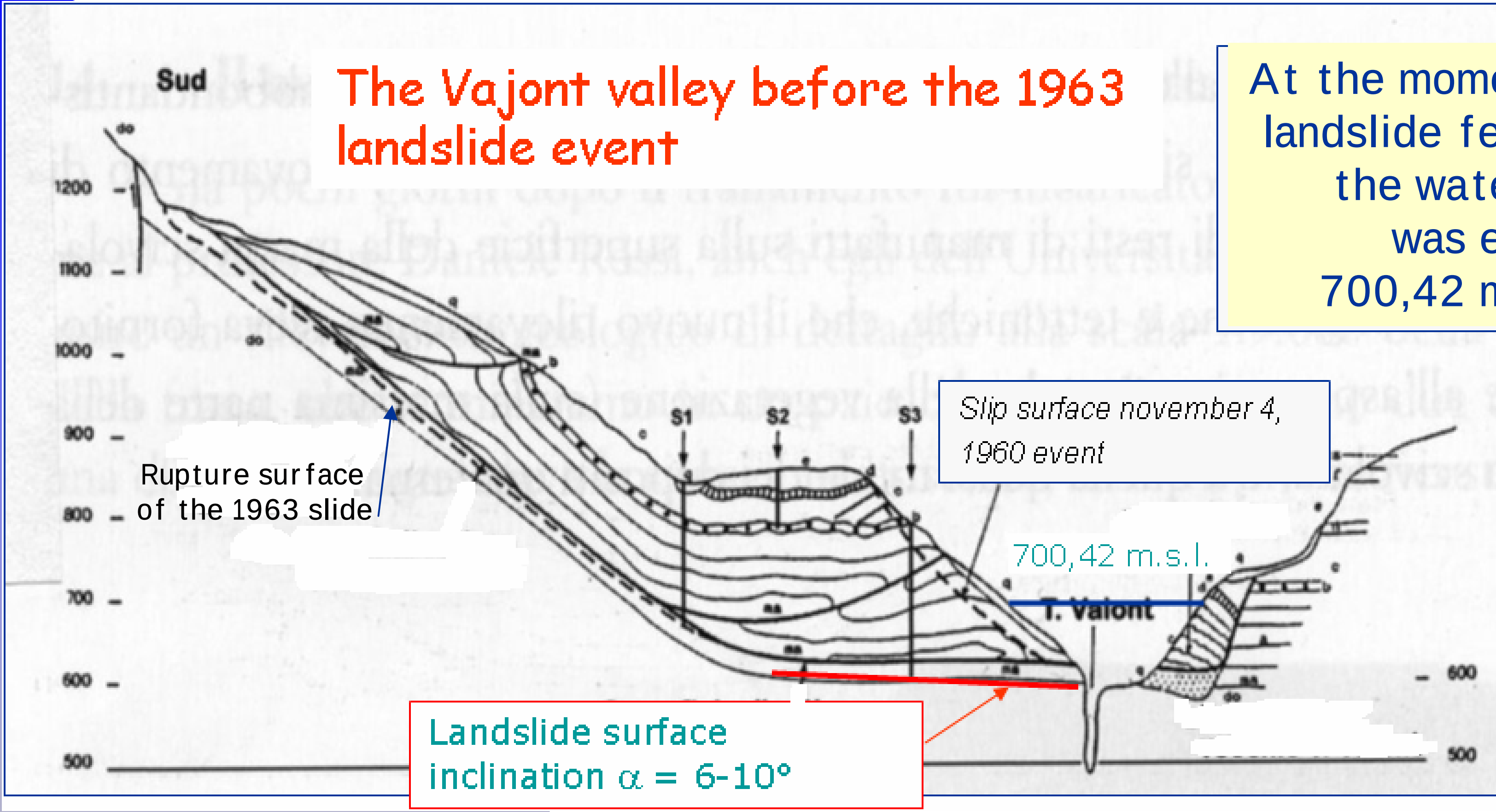
Vajont reservoir
October 9th, 1963 event

M-shape mechanism of the landslide



E. Semenza, October 10, 1963



At the moment the landslide fell down the water level was equal to 700,42 m on s.l.

Bearing in mind the aim of applying the experimental formulations to characterize the generated impulse waves, it is to be stressed that the considered event presented values of physical parameters well outside the experimental ranges. However, we believe that the application of the forecasting formulation can still provide useful and reliable information about the generated impulse wave.

Parameters introduced in the experimental formulation

Landslide width (w)	[m]	2000.0
Landslide height (h)	[m]	140.0
Impact velocity (v)	[m/sec]	20-25
Local water depth (d)	[m]	200.0
Angle from velocity vector (θ)	[°]	0.00
Landslide surface inclination (α)	[°]	6-10
Distance from impact point (r)	[m]	280.0
Runup slope inclination (γ)	[°]	25

h/d	*w/d*	*v/√(gd)*	α	θ	*r/d*
0.11÷0.45 **0.70**	0.75÷3.00 **10.0**	0.99 ÷ 2.22 **0.45 ÷ 0.56**	16° ÷ 26° **6° ÷ 10°**	0° ÷ 90° **0°**	1.31÷15.12 **1.41**

Slide non dimensional parameters

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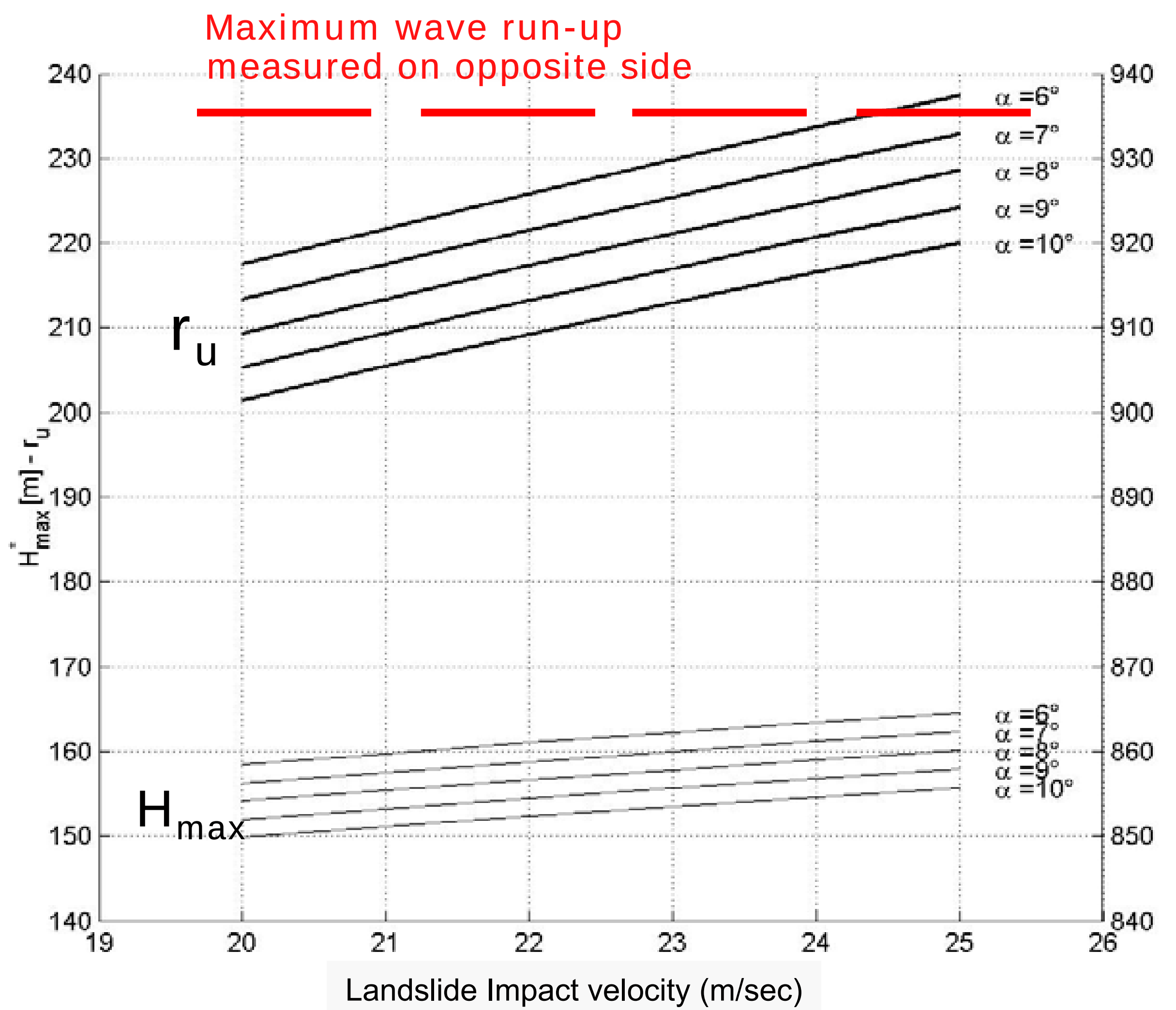
Vajont reservoir
October 9th, 1963 event



Application of forecasting formulation

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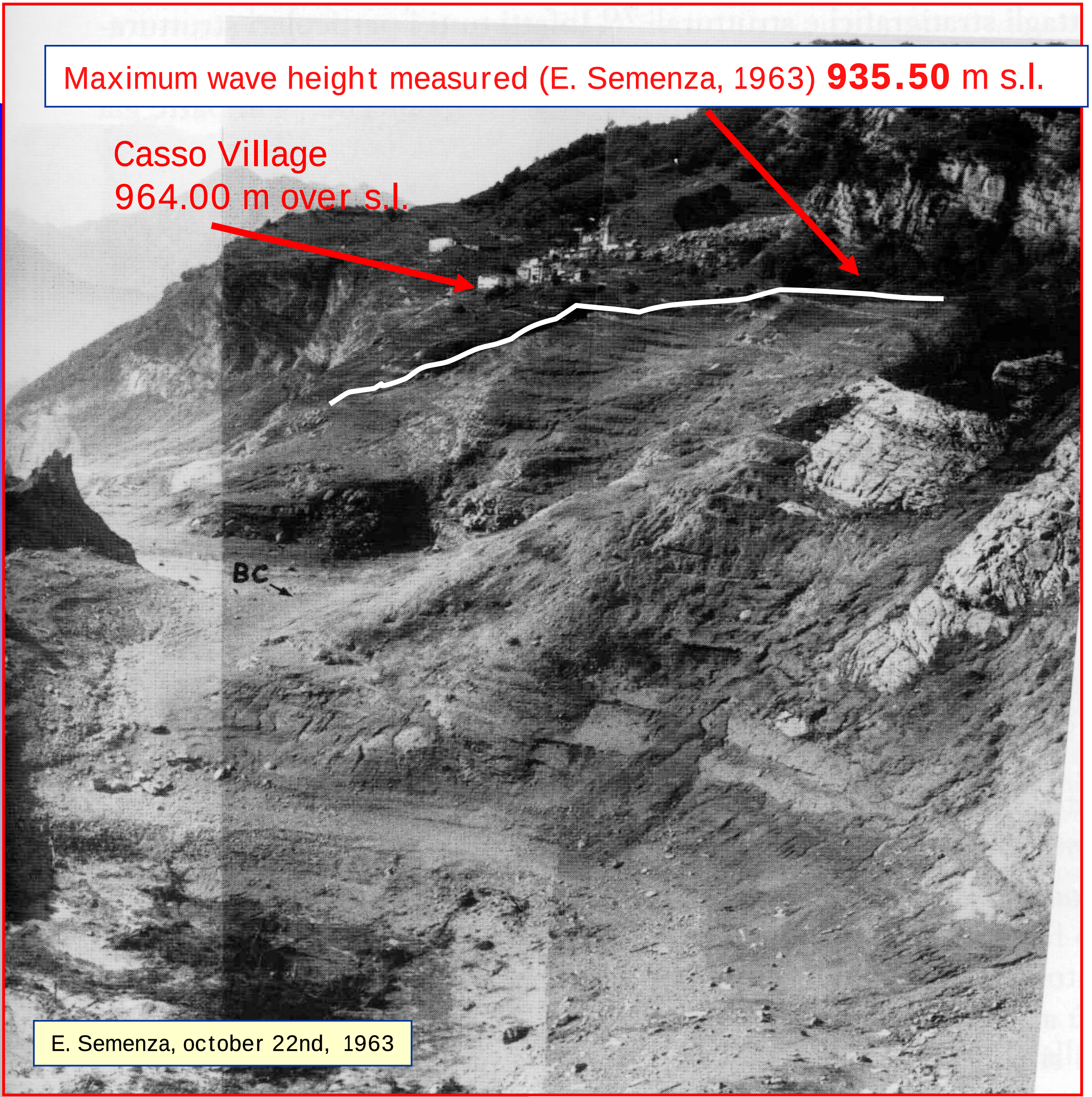
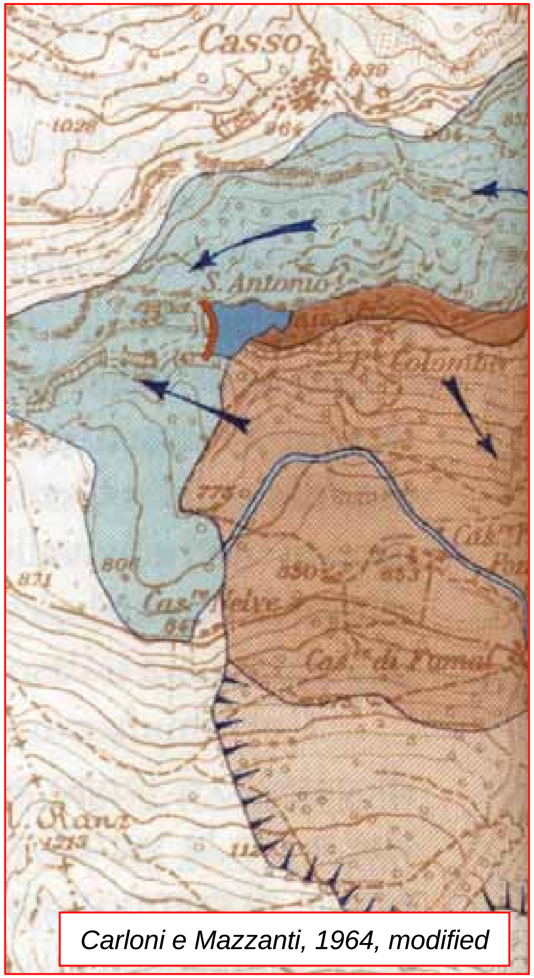


E. Semenza, october 22nd, 1963

Vajont reservoir
October 9th, 1963 event



Carloni e Mazzanti, 1964, modified

Conclusions

Part of the results obtained within the research program defined empirical formulation to forecast the principal features of the impulse generated waves as a function of the landslide mechanism.

These formulations have been here in the study of three famous and tragic event landslide generated waves occurred in Pontesei and Vajont artificial basins.

By making reasonable assumption about the landslide kinematical parameters, this work has shown that the considered empirical formulation well estimated the values of both the maximum generated wave height *Hmax* and the wave run-up r_u.
Observation of the reported events from the literature showed a very satisfactory agreement with the empirical formulations results.